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MULTIFUNCTION TDMA TECHNIQUES.(U)

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Final Technical Report
August 1976

MULTIFUNCTION TDMA TECHNIQUES

Ohio State University

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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APPROVED: Stuart H. Talbot
STUART H. TALBOT
Project Engineer

APPROVED: Fred I. Diamond
FRED I. DIAMOND
Technical Director
Communications and Control Division

FOR THE COMMANDER: John P. Huss
JOHN P. HUSS
Acting Chief, Plans Office

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This report presents a background discussion and general overview of the design of prototype equipment fabricated to demonstrate the feasibility of TDMA systems. Problems and options associated with the design of the equipment consisting of prototype TDMA modems and a satellite simulator which employs an adaptive null-steering array (ANSA) are presented in varying degrees of detail. Also, potential applications are identified and discussed briefly. As a result of the work performed during this contract it has been possible to definitely

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establish that TDMA and ANSA techniques are practical means for improving the efficiency and capability of satellite relay communications systems.

CONTENTS

EVALUATION

The primary objective of this effort was to design and fabricate prototype hardware to demonstrate the feasibility of Time Division Multiple Access (TDMA) and adaptive null-steering array (ANSA) technology for potential operational applications. Testing made possible by the prototype hardware has established that bit-synchronous TDMA is operationally feasible for satellite relay applications; that TDMA provides the capability of efficient network control; and that in addition to the TDMA system design being compatible with an ANSA, it is also the most economical way of employing one.

The results of this effort represent a portion of an integrated RADC effort for advanced satellite communications under TPO-10. The technology developed is applicable to the planning and design of future satellite communications systems.

Stuart H. Talbot

STUART H. TALBOT
Project Engineer

SECTION I
INTRODUCTION

Time Division Multiple Access Systems (TDMA) and Adaptive Null Steering Array (ANSA) Antennas have been under investigation for some time at the ElectroScience Laboratory under previous contracts with the United States Air Force [1-12]. The earlier contracts were concerned primarily with the basic principles of such techniques, their advantages and disadvantages for use in relay satellite communications systems, and the technology that must be developed in order to implement these methods into a practical system. The early work showed that TDMA and ANSA are in fact applicable to satellite communications systems and have many advantages to offer. The present contract was initiated for the primary purpose of building prototype hardware to demonstrate the feasibility of TDMA and ANSA Technology under actual operating conditions. As will be seen, the initial faith in these techniques has been amply justified. Hardware has been developed and built which performs as well or better than was anticipated at the start of this program. Performance tests have shown that the TDMA modems fabricated under this program have error rates which compare favorably with conventional communications systems; while the ANSA, built in the form of a satellite simulator, has shown itself to be both compatible with the TDMA format and capable of rejecting very high levels of interference.

A second objective of this program has been to investigate the advantages, problems and tradeoffs associated with multifunction communications equipment. Three major functions required of Air Force communications systems are: relay satellite communications, line-of-sight communications, and navigation. These functions have a number of characteristics in common. The type of information to be conveyed over a communications link is likely to be similar whether that link is line-of-sight or via a relay satellite. The possibility thus exists for employing similar modems in both types of link. The use of TDMA in satellite communications requires an accurate knowledge of the range from the satellite to the various terminals in order that the necessary timing relationships may be established between the various transmissions. However, this piece of information is precisely what is needed by a navigation system in order to determine the position of a terminal in relation to a number of satellites. The possibilities of multifunctional equipment have been studied to some extent as a part of this program, and the goal of multifunctional use has been kept in mind in the prototype system development.

SECTION II
BACKGROUND

The advent of satellite communications brought with it a number of problems which had not previously received sufficient attention. Two in particular are of major importance: efficient usage of the satellite resource, and avoidance of interference. A satellite has only limited power available. This means that the output power of its transmitter is also limited, which in turn limits the available bandwidth for a given transmit signal-to-noise ratio. To make best use of the satellite resource it is necessary that most of this bandwidth be used most of the time. The old system of dividing the available bandwidth by frequencies (frequency division) into a number of narrower band channels and assigning these channels on a one-per-user basis (or even sharing a channel between several users), is not efficient unless all the users are transmitting almost continuously, a situation which does not usually prevail. Another serious disadvantage of the frequency division system becomes apparent when it is realized that a large variety of ground and mobile terminals may be communicating via the same satellite. This variety can result in widely different signal levels being received at the satellite. This in turn can produce cross modulation of signals on different channels, saturation of the satellite receiver by strong signals, and possibly complete exclusion of the weaker ones. The TDMA approach offers significant advantages in dealing with these problems. With this method the satellite resource is shared among the various users on a basis of time rather than frequency; the entire bandwidth of the satellite relay is available to each user during his turn. From a practical standpoint, time is an easier resource to share among a variety of users than is frequency. It is relatively simple to assign a small amount of time to a terminal requiring only a low average data rate, for example a teletype, and a much larger amount to one requiring a high average data rate, such as a digital computer. The other major advantage of the TDMA system lies in the fact that all users transmit on the same frequency and only one transmits at a time. The problems of cross modulation and domination of the link by the more powerful terminals is thus avoided. Of course a new problem is introduced which was not present in the frequency division system, that of timing the various transmissions so that only one is passing through the satellite at a time. A major purpose of the present program has been to show that this sharing of the available time can be managed successfully.

Turning to the interference problem, a satellite in synchronous orbit is visible over the greater part of a hemisphere of the earth. This is obviously desirable from the communications standpoint since it permits transmissions between terminals anywhere within this area. However, it also means that the satellite is exposed to potential interference, either accidental or deliberate, from anywhere within the same area. ANSA antennas offer a powerful tool for dealing with this problem. The ANSA antenna is a multielement antenna with each element generally having a radiation pattern designed to cover the area of interest. The signals

received by the various elements are summed. However, instead of summing them with a fixed phase and amplitude relationship, as with a conventional array, the phase and amplitude of the output from each element is adjusted automatically before summation takes place. By appropriate adjustment of the phase and amplitude settings, pattern nulls and maxima may be placed in various directions. Obviously the desired condition is to place beam maxima in the directions of desired signals and nulls in directions from which interference is coming. This automatic adjustment is performed by means of a closed loop servo system, in response to the various incoming signals. Implementing an ANSA in a frequency division system presents serious problems: the array must form simultaneous beams in the directions of all desired signals being received by the satellite, in addition to forming a null in the direction of arrival of any interfering signal. If there are a large number of simultaneous users, this can add considerably to the complexity of the array since, as a rule of thumb, there must be one more element in the array than the combined number of beams and nulls to be controlled. A further difficulty arises when additional users start to use the system after the satellite antenna pattern has been formed. It is conceivable that the new user might transmit into a null or near null and so not be recognized by the system.

The combination of an ANSA with a TDMA system removes most of these problems. In the case of TDMA only one desired signal is ever being received by the satellite at a time, thus only one beam maximum need be formed by the ANSA. In addition, since messages are transmitted in discrete time slots, the ANSA control system may be made cognizant of the times at which a desired signal may be expected to arrive from a new direction. The ANSA may be designed to revert to a uniform earth-coverage radiation pattern at these times. Then, if the response time of the array is fast enough and a suitable preamble is provided at the start of each message package, the ANSA can form an entirely new radiation pattern during this preamble period to accommodate the new source, while suppressing any interfering signals which are currently present. This has been the guiding concept in the design of the satellite simulator under the present program. This simulator has been designed to accept the TDMA format and to imitate the performance of an ANSA on board a relay satellite.

SECTION III
THE TDMA MODEMS

Before beginning the design of the TDMA modems a number of fundamental decisions had to be made. If individual users are to transmit at precisely controlled times some form of clock is necessary. One possibility is for every user to have a very accurate clock. However, such an approach did not appear practicable, particularly for mobile users, because of the difficulty of maintaining sufficient accuracy and the necessity for at least occassional resynchronization. The only reasonable choice was to provide a single clock shared by all users. The logical place for such a clock is in the relay satellite, since it is the only part of the system which is present in all links. However, since this was to be a prototype system and no satellites with clocks on board are now available, it was evident that at least one of the ground terminals must be provided with a clock which could be transmitted via the satellite to all other users. The second basic requirement was for a network control station able to assign time slots to the various would-be users as demand, availability and priority considerations dictated. Such a function is relatively complex and prone to policy changes. It thus appeared inappropriate to assign such a function to the relay satellite where it must be largely automatic. Also there was still the problem of unavailability of any satellite capable of performing such a function. Thus again it appeared that at least one ground terminal must be capable of performing the network control function.

These initial considerations led rather naturally to the master and slave concept, with one master station providing the clock and network control functions and a number of slave stations capable of communicating with each other and with the master station. The idea of a single master station has, however, a number of drawbacks. If the master station should fail for any reason, such as an electrical defect or military action, then the entire network would be out of service. In addition it may be desirable to divide up the total satellite resource into a number of parts, each of which is assigned to a different network control station. These two factors together suggested that at least several of the modems should be capable of performing the master function.

A study of the various functions which both master and slave stations must perform and of the major components necessary to implement them led to the conclusion that the requirements were almost identical in the two cases. The decision was therefore made that all of the prototype modems should be the same, with the provision that a minicomputer would be required at any location to be used as a network control station to perform the extra bookkeeping functions which could not readily be handled within the capacity of the modem digital controller.

Figure 1 shows a block diagram of the design resulting from these conclusions. Detailed drawings of the various components have been delivered as a separate item under the contract. Figure 2 shows a photograph of a finished modem. Four such modems were constructed and delivered under this contract. Their operational details have already been discussed in References 13 and 15 and will not be repeated here. However a diagram

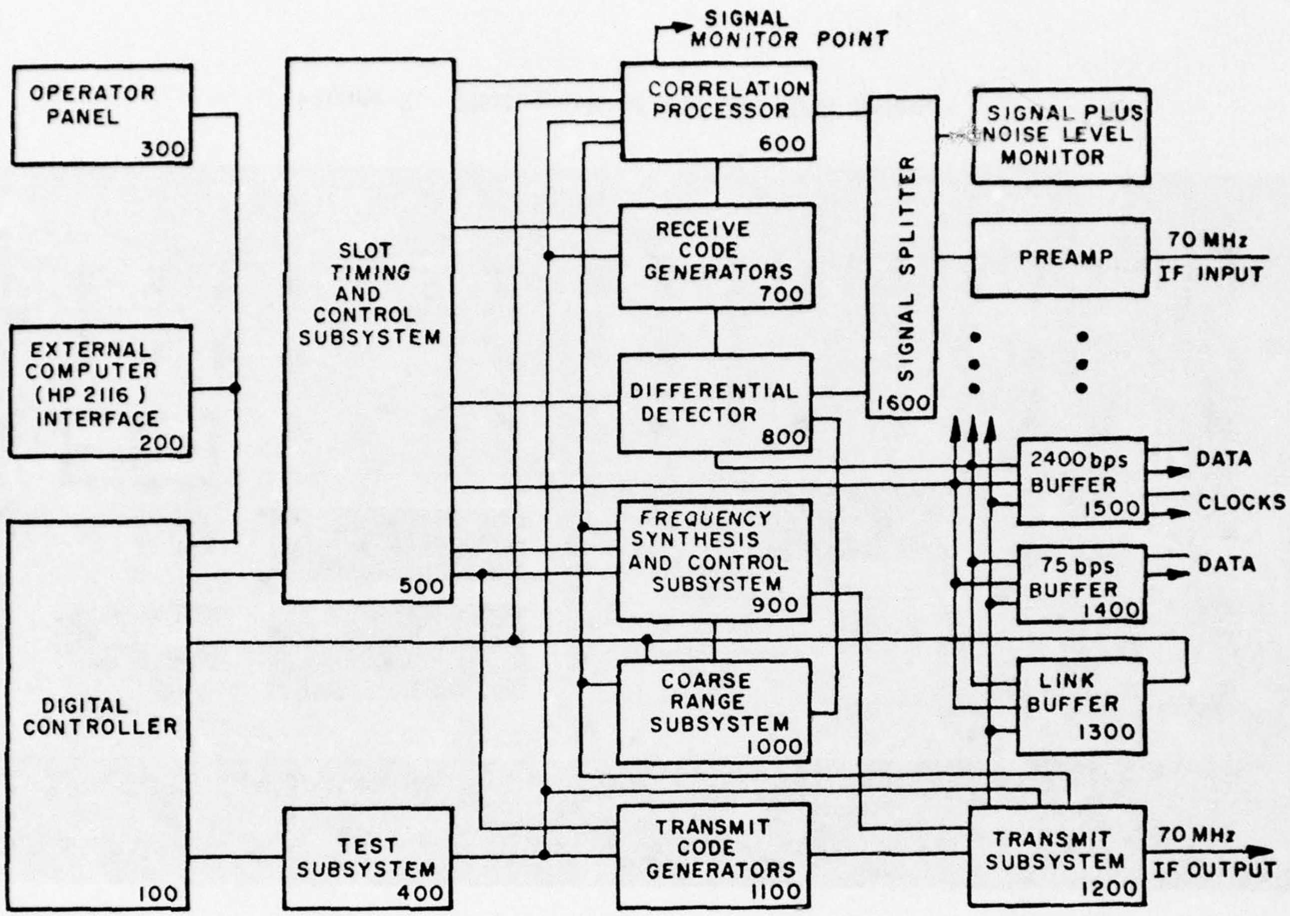

Figure 1. Block diagram of the OSU TDMA modem.

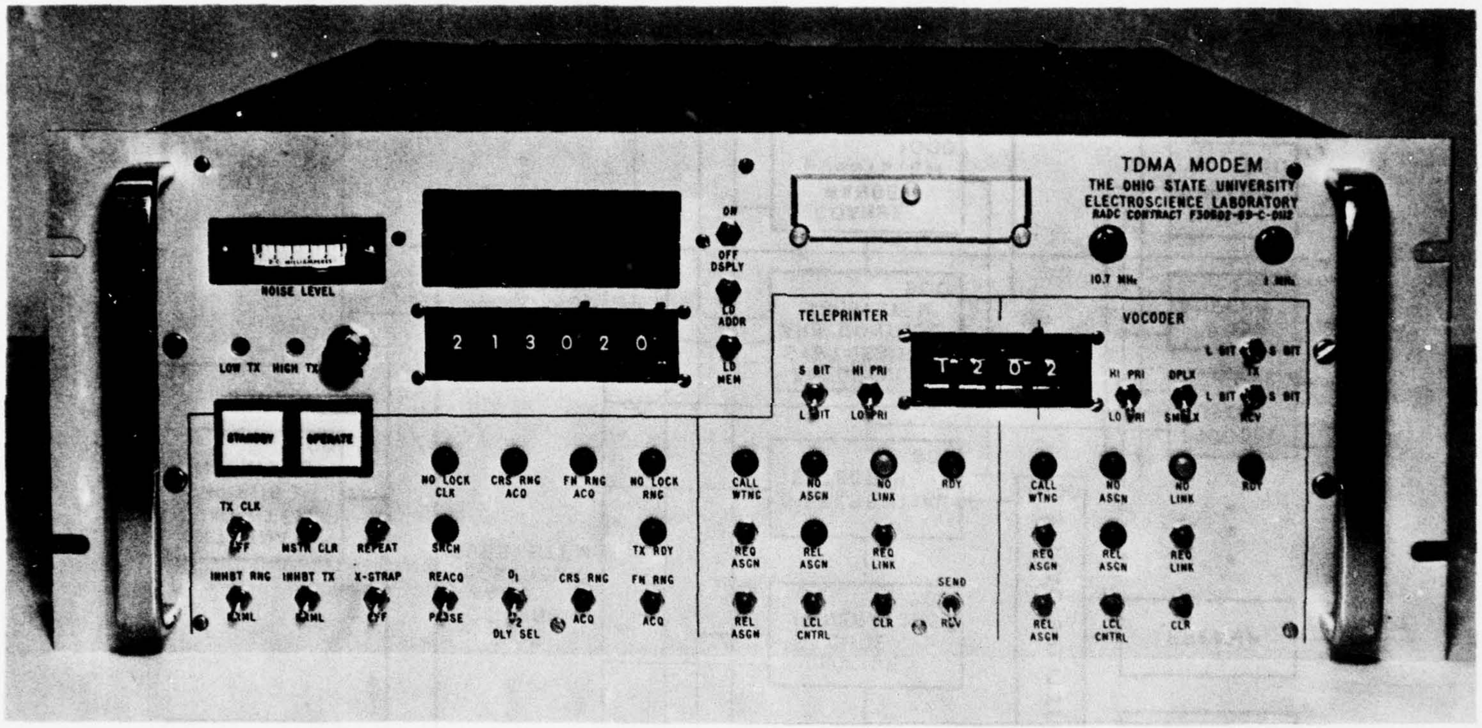

Figure 2. Photograph of the OSU TDMA modem.

of the format employed for data transmission is shown in Figure 3 and will be discussed briefly. The format is based on a frame which has a duration of 32/75 sec. The entire sequence of slot assignments is repeated every frame, unless of course there happens to be a change in network usage. The start of each frame is identified by a double clock pulse. Two format rates are available. In the high rate format (HRF), which requires a system bandwidth of approximately 4 MHz, each frame is divided into 128 subframes. In the low rate format (LRF), requiring a bandwidth of approximately 500 KHz, each frame is divided into 16 subframes. The start of each subframe is identified by a single clock pulse. Each subframe is, in turn, divided into 32 data slots. For want of a specific network model, the somewhat arbitrary decision was made to allocate one quarter of the slots in each subframe, that is to say eight, to network management and the remainder to message transmission. The normal data rate is eight bits per slot. An optional rate of 64 bits per slot is available in the LRF only, for terminals having a signal-to-noise density ratio of at least 60 dB. The TDMA modems are designed to handle two message rates: a 75 bits per second rate intended for teletype use and a 2400 bits per second rate intended for vocoders (digital voice encoders and decoders). In the HRF, for example, an assignment of one slot per subframe would be required to accomodate a 2400 bps transmission, while one slot every 32 subframes could handle a 75 bps rate. Obviously 32 teletype channels can be accommodated in the same time slot allocation as would handle one vocoder channel. The different types of transmissions can be accommodated in essentially any combination up to the total capacity of the system. The same is true for the LRF except that the total system capacity is smaller than for the HRF. The first eight slots of each subframe are used for network management. Pairs of slots, identified in Figure 3 as link-range pairs, are permanently assigned to each user. By transmitting appropriate codes in these time slots the user may first request a data slot assignment from the network controller, and then request linking with another terminal using the assigned slot or slots. The link-range slots are also used to estimate the range to the relay satellite by transmitting an appropriate code in this slot and measuring the round trip transit time. This information is necessary in order that the user may transmit with the appropriate lead time so that his transmission will arrive at the relay in the correct time slot. Transmitter timing is repeatedly corrected to allow for possible motion of the relay and the user.

A pseudo noise (PN) code is impressed on the transmissions. This is done normally at a rate 16 times faster than the data rate; but twice the data rate is used for the PN code when 64 data bits per slot are transmitted in the LRF. A different PN code is used for the clock pulses for identification. A bandspreading factor of 16 is sufficient to minimize degradations due to multipath effects and moderate-level interference.

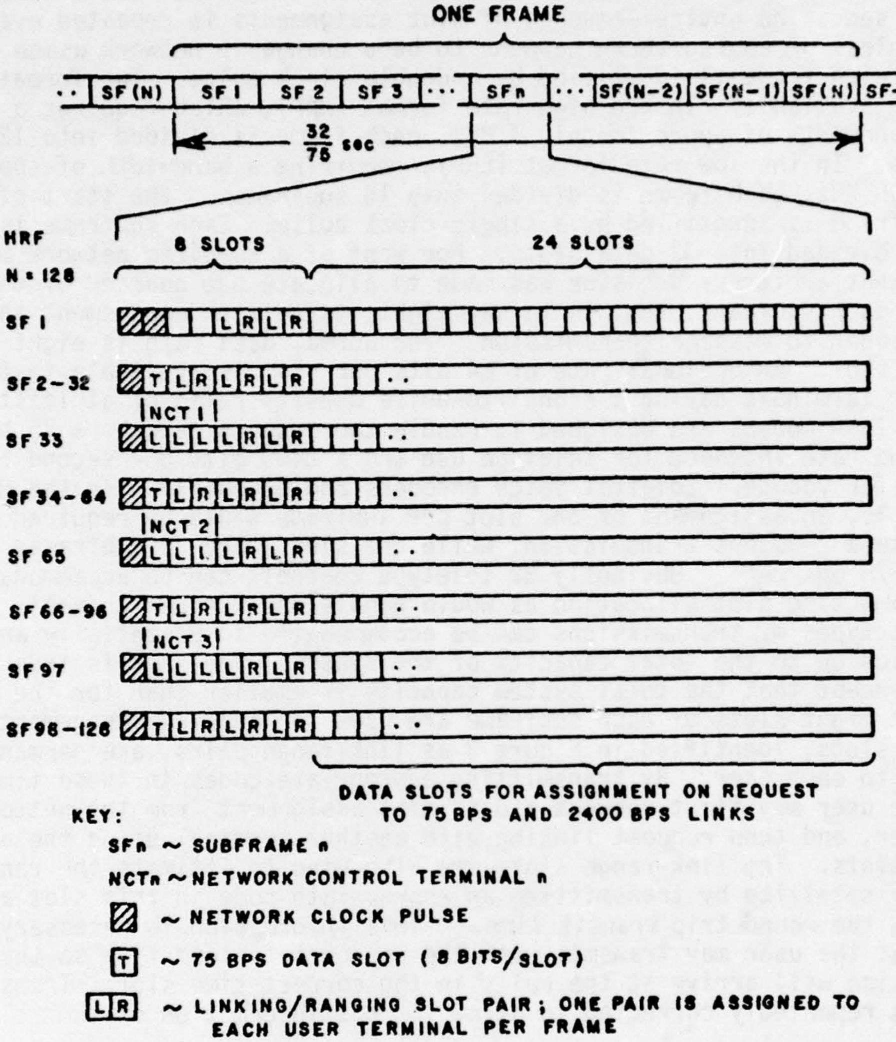

Figure 3. The TDMA modem signaling formats.

Communication between the modems and the various message generating and receiving devices (teletypes, vocoders, etc.) is at a rate appropriate to the device in question. Buffering is provided by the modems to permit a continuous data stream between it and the various devices, even though the TDMA concept requires that the data be packaged and transmitted in high rate bursts over the relay link. Communication between the modems and the r.f. receivers and transmitters is at a frequency of 70 MHz.

Tests performed at the RADC test facility at Verona in November, 1974, showed excellent results. The bit-energy to noise-density ratio required to establish a given bit error probability was found to exceed the theoretical value by only 0.3 dB, a performance rarely achieved in operational equipment.

SECTION IV
THE SATELLITE SIMULATOR

The objective of this portion of the program was to build a simulator which would effectively demonstrate the performance of an ANSA combined with spread spectrum signal processing as these techniques would be used in a relay satellite. As was discussed in Section II, a relay satellite can be very vulnerable to interference on the up-link because of the inherently wide coverage of its receiving antenna. An ANSA offers a potential means of solving this problem. In turn, the use of a TDMA format appears to be the only economical way of employing an ANSA. With TDMA only a single antenna beam need be formed at one time. With a frequency division system a separate beam must be formed for each channel, which adds greatly to the complexity of the ANSA and the associated signal processor and must severely limit the number of channels which it is practicable to service at one time. The present simulator was therefore designed to operate with TDMA and to be compatible with the modems which were built as part of this program (see previous section).

There were two major objectives in the development of the satellite simulator. One of these was to achieve a response time compatible with the TDMA format. To be workable the ANSA must form a new beam at the start of each data slot, or group of data slots if several consecutive slots are assigned to the same user. Obviously the array cannot adapt in zero time. One data slot width was therefore allocated for this purpose. This reduces the available data capacity somewhat. In the worst case the loss would be fifty percent if every slot available for data transmission were assigned to a different user. Half the slots would then be required for ANSA adaption. With a mix of users, in which many are assigned several consecutive slots, the loss would not be significant. The other objective was to design a system which can respond to a desired signal much lower in level than interference received concurrently with it.

Investigation under the preceding contract determined that spectrum spreading combined with correlation processing is a practical means of generating a reference signal. This reference signal can then be used to control the weights of the elements of the ANSA so as to favor a signal resembling the reference, while tending to reject all others. An experimental system has been implemented using these principles. Figures 4 and 5 illustrate the essential features of the ANSA control system and the reference signal generating circuit respectively. The system is based on the least-mean-square error (LMS) algorithm, sometimes referred to as the Widrow algorithm.

A very detailed theoretical and experimental study of this type of system was carried out under the present contract [14]. The results of this study are favorable. One serious problem was found which degraded performance and required solution. Referring to Figure 4, when the error

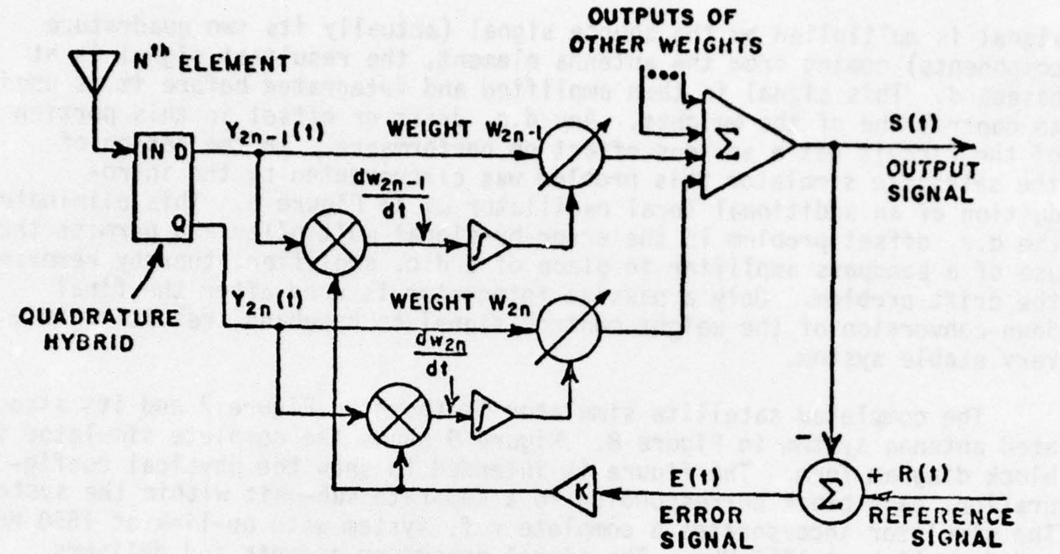

Figure 4. Basic diagram of the adaptive null-steering array processor.

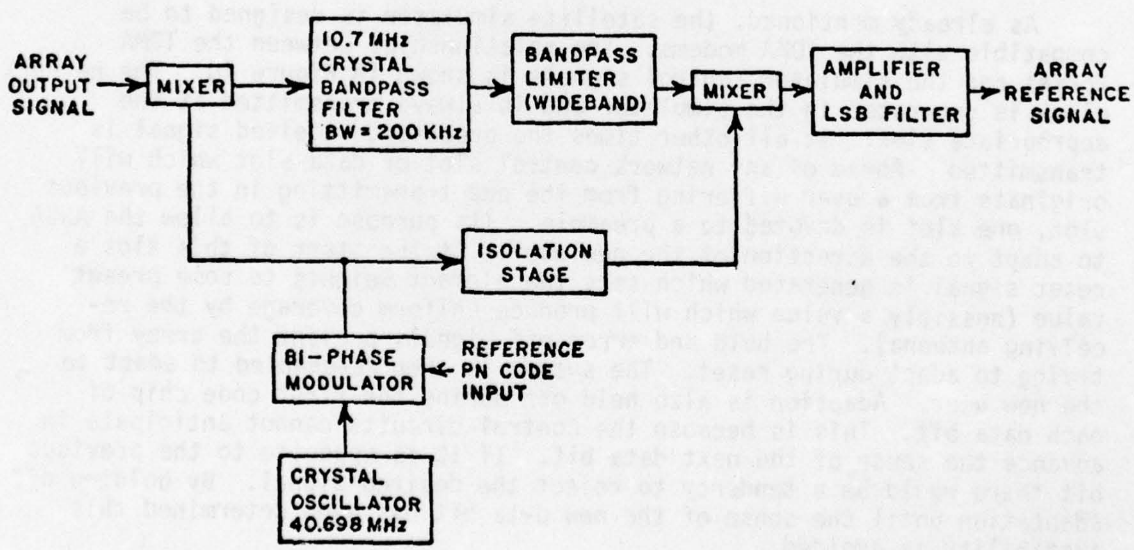

Figure 5. Block diagram of the waveform processor used to generate a reference signal from the array output signal.

signal is multiplied by the source signal (actually its two quadrature components) coming from the antenna element, the resultant signal is at baseband. This signal is then amplified and integrated before it is used to control one of the weights. Any d.c. drift or offset in this portion of the circuit has a serious effect on performance. In the design of the satellite simulator this problem was circumvented by the introduction of an additional local oscillator ω_1 in Figure 6. This eliminates the d.c. offset problem in the error-by-signal multiplier and permits the use of a bandpass amplifier in place of a d.c. amplifier, thereby removing the drift problem. Only a passive integrator is used after the final down-conversion of the weight control signal to baseband, resulting in a very stable system.

The completed satellite simulator is shown in Figure 7 and its associated antenna system in Figure 8. Figure 9 shows the complete simulator in block diagram form. The figure is intended to show the physical configuration, each block corresponding to a separate sub-unit within the system. The simulator incorporates a complete r.f. system with up-link at 1650 MHz and down-link at 1550 MHz. The signal processor accepts and delivers signals at 70 MHz and can be used with any r.f. system having suitable up and down converters. The satellite simulator is described in detail in Reference 16, together with operating procedures and performance characteristics. A theoretical and experimental analysis of the simulator characteristics has been completed and will be presented in a report now in preparation [17].

As already mentioned, the satellite simulator is designed to be compatible with the TDMA modems. The relationships between the TDMA format and the simulator control signals is shown in Figure 10. The network clock is generated in the simulator and is always transmitted at the appropriate time. At all other times the processed received signal is transmitted. Ahead of any network control slot or data slot which will originate from a user differing from the one transmitting in the previous slot, one slot is devoted to a preamble. Its purpose is to allow the ANSA to adapt to the direction of the new user. At the start of this slot a reset signal is generated which sets the element weights to some preset value (possibly a value which will produce uniform coverage by the receiving antenna). The hold and error-off signals prevent the array from trying to adapt during reset. The system is then re-enabled to adapt to the new user. Adaption is also held off during the first code chip of each data bit. This is because the control circuits cannot anticipate in advance the sense of the next data bit. If it is opposite to the previous bit there would be a tendency to reject the desired signal. By holding off adaptation until the sense of the new data bit has been determined this instability is avoided.

Initial tests of the simulator show it to be capable of suppressing a CW interfering signal which is 40 dB above the desired signal by more than 80 dB. The adaptive spatial processor (ASP) which controls the ANSA

can handle an interference-to-signal ratio which is 20 dB greater than could be handled by the earlier model of Figure 4. This improvement is directly attributable to the introduction of the additional i.f. stage in the error-by-signal multiplier. A further increase of at least 10 dB should be obtainable by optimization of the i.f. gains within the control loops. These tests were performed using 70 MHz inputs to the simulator; the r.f. circuits were not used. Tests of the entire system, including the antennas, are recommended below. The simulator has already been tested for compatibility with the TDMA modems in the low rate format, and it should also be compatible in the high rate format.

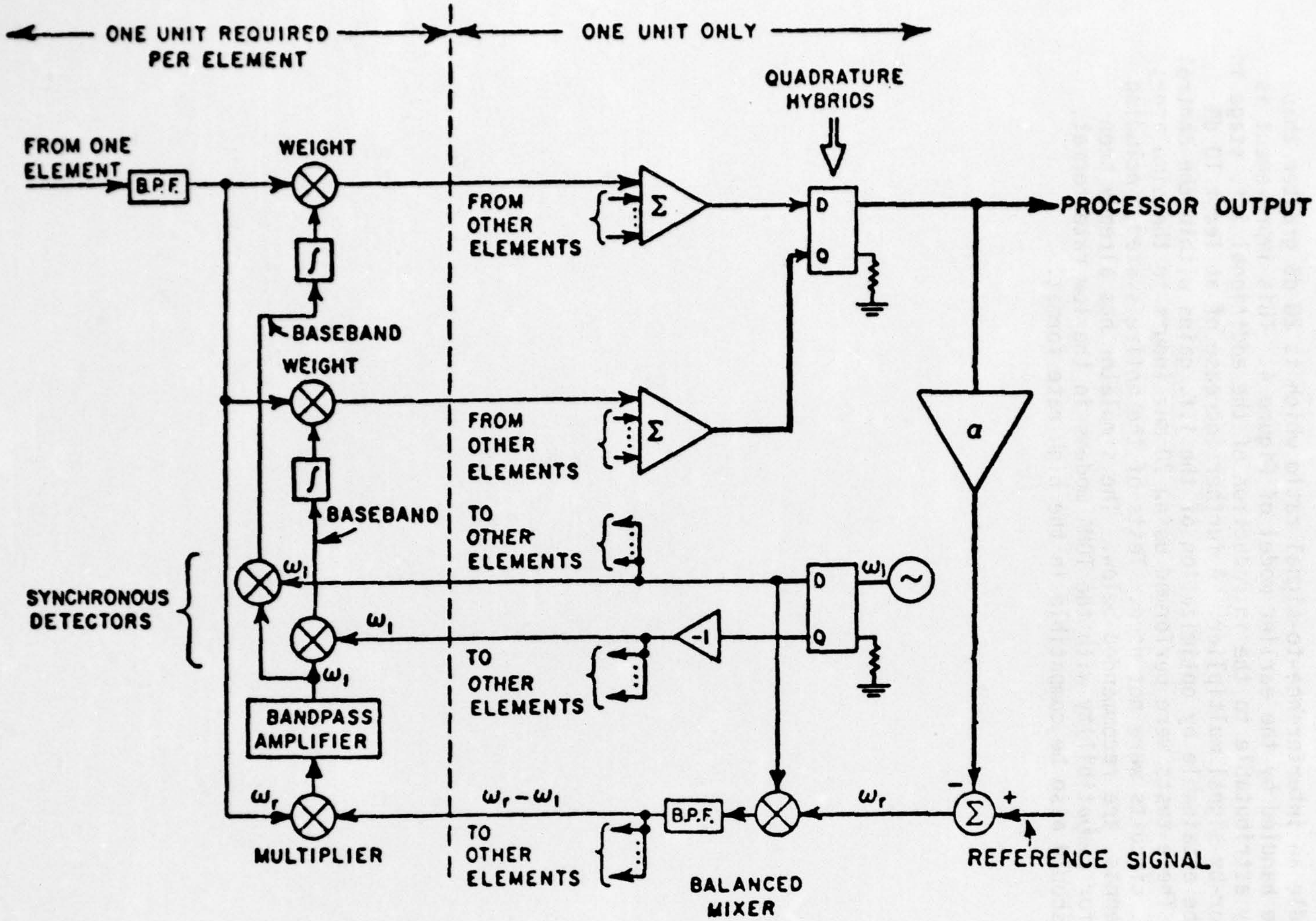

Figure 6. Functional diagram of the present ASP.

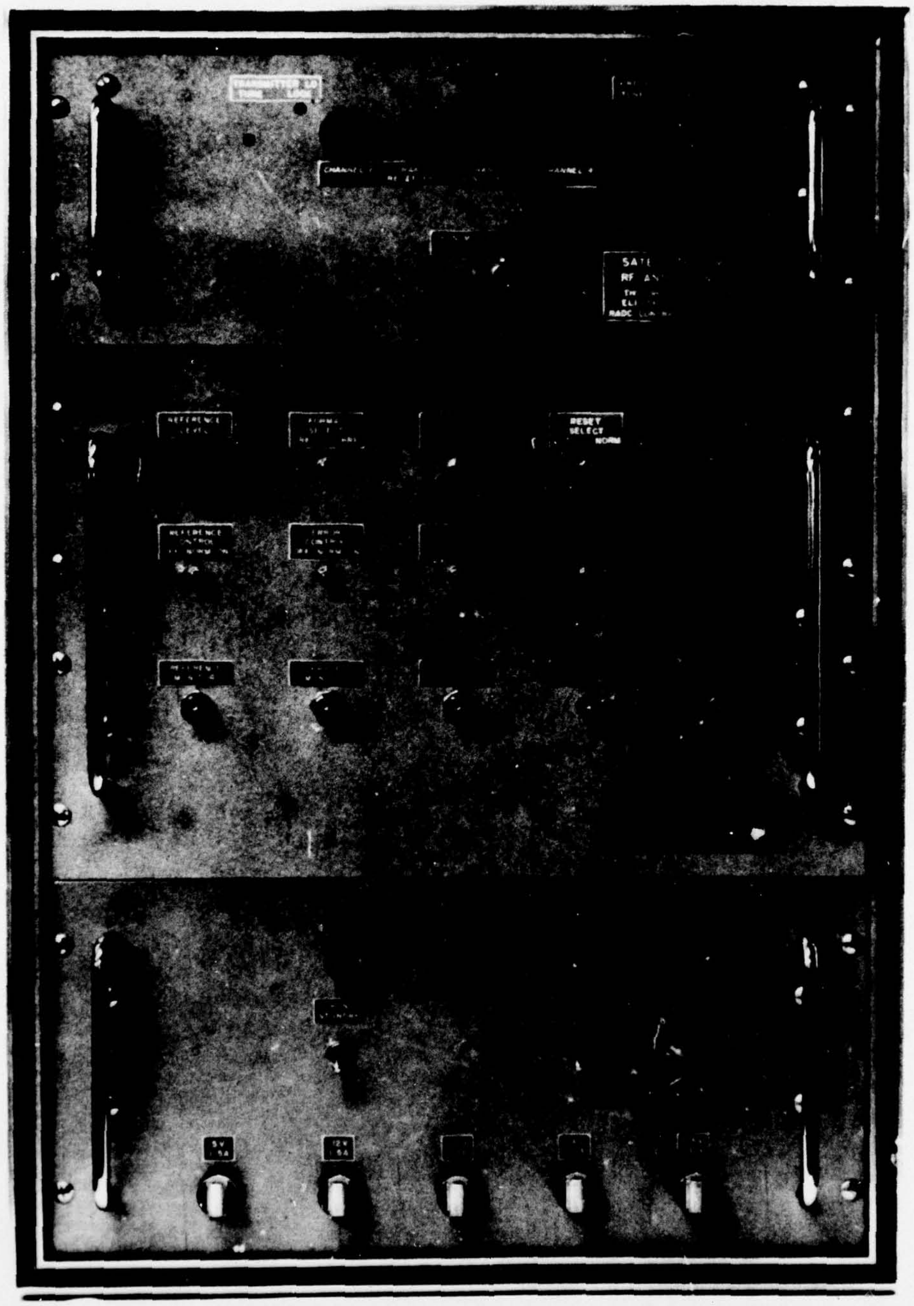

Figure 7. Front view of the satellite simulator.

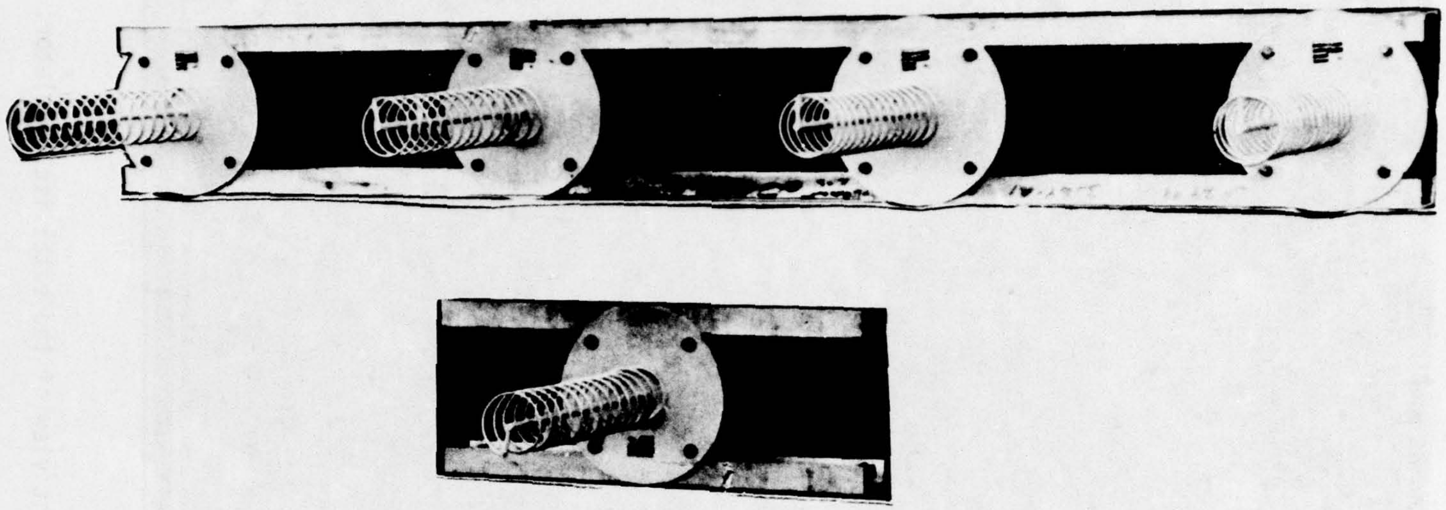

Figure 8. Receive and transmit antennas.

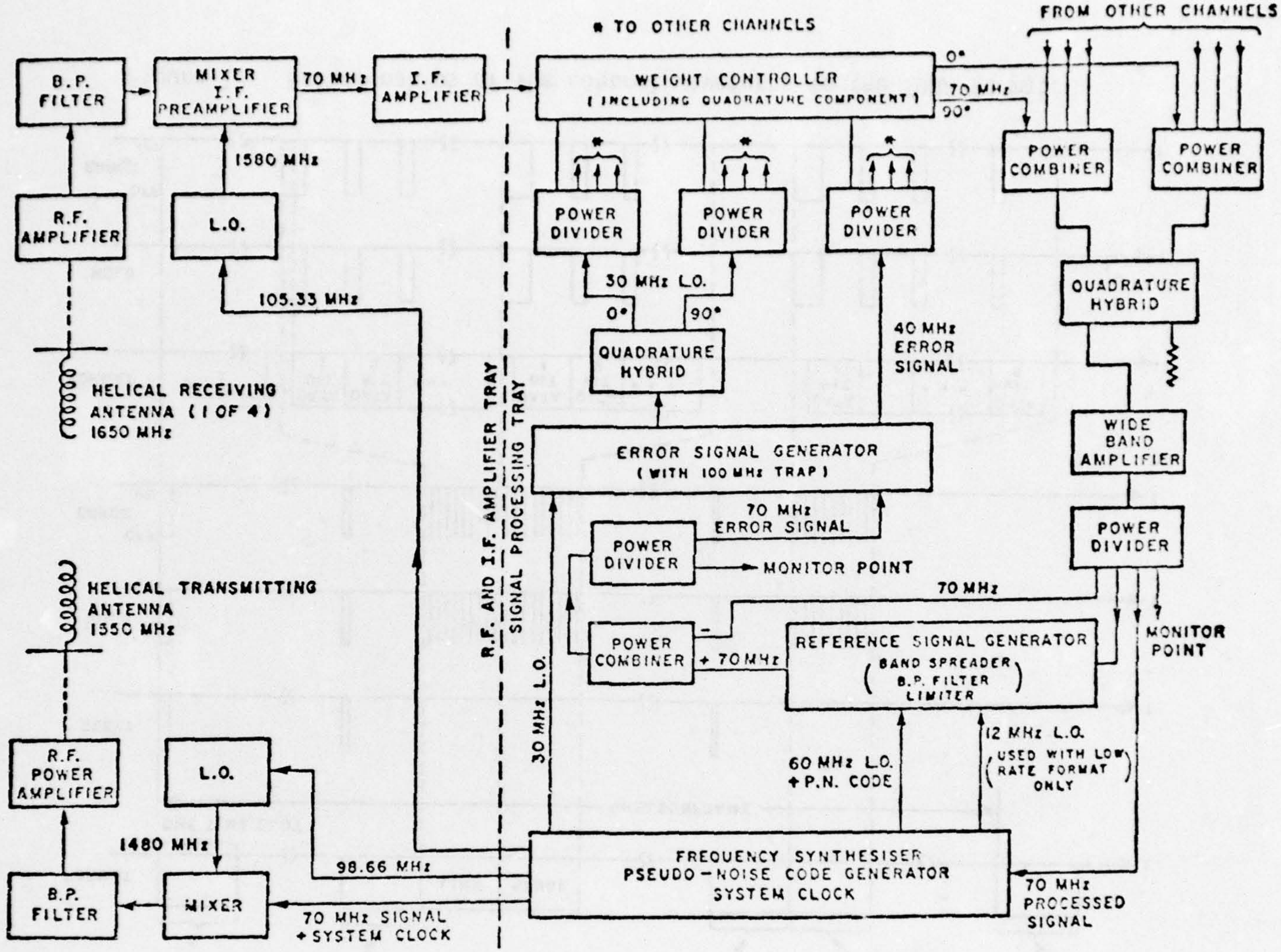

Figure 9. Block diagram of the satellite simulator.

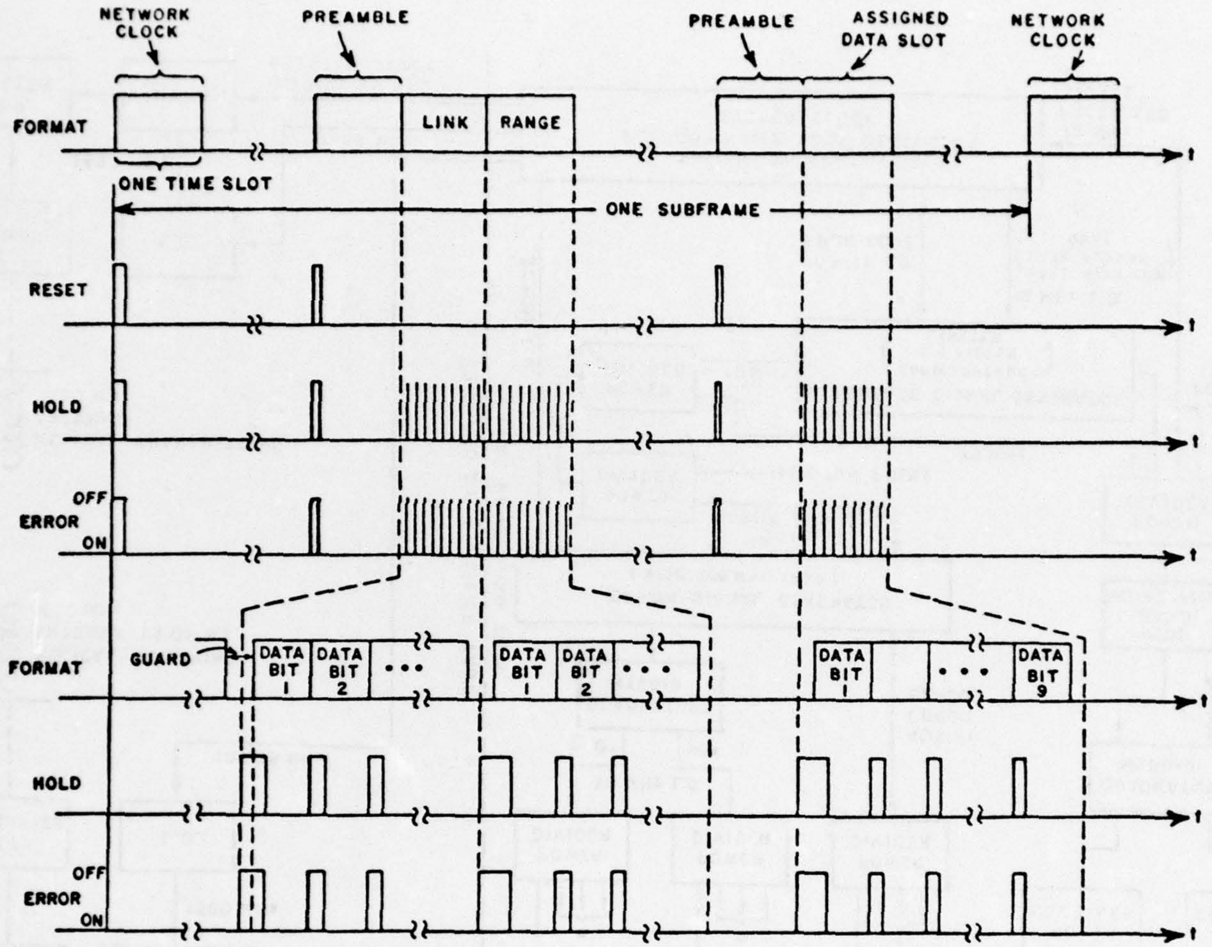

Figure 10. Relationships of the control waveforms to the TDMA format.

SECTION V
MULTIFUNCTION TDMA TECHNIQUES

While the major effort under this contract has been on the design and construction of the TDMA modems and the satellite simulator, consideration has also been given to the problems and possibilities of multifunctional systems. The TDMA system is ideally suited to relay satellite systems. It can also work with any other network employing a common relay station - on the ground, in an aircraft or in a remotely piloted vehicle (RPV) - provided that the relay is visible to all potential users. The question arises as to how well TDMA will work for direct line-of-sight communications between a number of independent terminals. Provided terminals share a common clock, there is a possibility for orderly management. However, as long as signals may arrive at a given receiving terminal from more than one direction, the possibility exists of more than one arriving at the same time, with consequent loss of information. If all users in a given network are located within a relatively small area one possibility is to assign a guard space between each active pair of data slots, equal in length to the transit time between the most distant pair of stations in the net. This will ensure that there is no overlap in transmissions and, if the distances between users are not too great, will not cause too great a loss of network capacity.

Since the TDMA modems must determine the transit time to the relay satellite to a high degree of accuracy in order to establish the correct transmission time, and since transit time is directly related to range, they are already performing the basic function necessary for navigation. If a station can measure the transit time or range to three different satellites, whose positions are accurately known, then the station's position can be determined. An alternative method involves measuring the difference in the transit times to four different satellites rather than the absolute time to three. Such a method requires a group of three or four satellites rather than the single one required for a communications relay. However, the remaining satellites could be of simpler design if intended only for navigation purposes.

These topics are discussed further in References 13 and 15.

SECTION VI
CONCLUSIONS AND FUTURE WORK

The work performed under this contract has established definitely that TDMA and ANSA techniques are practical means of improving the efficiency and immunity to interference of satellite relay communications systems. It has been proved that signal timing can be established with sufficient accuracy to make TDMA work. It has also been shown that TDMA largely eliminates the problems of inefficient network usage and mutual interference between desired signals associated with frequency division systems. In addition TDMA makes the use of an ANSA practicable as a means of reducing interference on the up-link. It has been demonstrated under this contract that very substantial interference reduction is possible by this method.

It also appears, based on the results of this program, that there are significant benefits to be gained by the use of multifunctional systems under appropriate conditions. It has been shown that TDMA is workable for line-of-sight communications with certain reservations, in particular that the range between terminals is not too great. The basic parameter required for navigational purposes is inherently present in the TDMA system, namely an accurate measure of the transit time between the relay satellite and a user station. Whether or not there are economic and technical benefits to be gained by combining these functions in a single piece of equipment appears to depend greatly on the missions which that equipment is intended to serve.

As regards the future, there are still significant questions to be answered as a necessary step in the design of operational systems. More tests need to be performed on the satellite simulator using radiated r.f. since the initial tests were performed with hard-wired connections. In addition, consideration needs to be given to steerable down-link beams, multiple satellite antenna beams, satellite-to-satellite links to extend the coverage of the net, and the possible incorporation of more processing in the satellite to simplify the user terminals. The use of relays other than satellites also needs investigation; for example an RPV, balloon or aircraft.

The present TDMA modems are a mixture of digital and analog circuits. With recent advances in digital technology it would now be possible to replace many of the analog circuits with digital equivalents. This would simplify production and allow more efficient packaging. Extension of the spectral width which the modems are able to handle, from the present 10 MHz to 50 MHz, is also desirable. Such a change would permit the handling of a moderate number of medium to large terminals instead of a large number of small ones. Another feature which would increase modem versatility would be the ability to change the transmission format under program control, rather than being limited to two manually selectable formats as at present.

Bit-synchronous TDMA will undoubtedly become one of the communications systems of the future, and the present program has proved its feasibility.

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